Settlement Upon Venus

A Comprehensive Plan for Establishing a Permanent Human Presence, High within the Atmosphere of Planet Venus

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Background — The Cosmos

Dr. Carl Sagan, with his groundbreaking original Cosmos series, had a huge impact on my thinking early in life. I remember that he conveyed a message, consistently throughout the series, of an urgent concern for the survival of the human species. While imagining the promises of a science-based human future, he would also remind us that we humans now, gravely, have acquired the power to make the earth unlivable in part or in whole —this either by deliberate action (example nuclear war) or by accident (example runaway greenhouse effect). Things have *not* always been this way; our collective foolishness has never before had this immensity of power backing it.

Sometimes people comment that we should terraform other planets in order to have a backup if we destroy this one. I've got news, terraforming planets would be way more difficult in reality than it is in science fiction. Anyway, if we can't even *stop ourselves* from transforming our own paradise planet into a poisonous rock, there is for sure no way we could transform a poisonous rock into a paradise planet.

So, this study on the possibility of sustained human habitation, within the atmosphere of planet Venus, is likewise predicated with grave caution. However, assuming we do the hard work, at least to figure out how to just get along... and start doing much less destroying overall...

Background — Space Bases

As humans become truly space-fairing, there will no doubt be manned outposts on Moon and Mars, and both probably long before any real attempt to settle Venus. However if looked at from an economic point of view, Moon and Mars have limited resources available, and so limited potential for trade within the solar system.

Like Venus, Mars has an atmosphere that is mainly carbon dioxide —CO_2. However, the atmosphere of Mars is so thin that in practice it would be difficult to extract useful amounts of CO_2. It is indeed useful, too; it is needed for growing plants, and when combined with an energy source it can be cracked into oxygen and elemental carbon. Meanwhile, Venus has so much CO_2 that the weight of it would crush (and has) nearly any human technology which would attempt to reach the surface. Ordinary molecular nitrogen (N_2) makes up 3% of Venus' atmosphere, small compared to Earth's roughly 78%, but it is still enough to extract effectively. Molecular nitrogen is essential for formulating

fire-safe, easily breathable air mixtures. Moon's lack of an atmosphere can itself be considered a resource, allowing manufacturing in vacuum, while still within the context of a well-defined "down" direction.

Even if only orbital solar energy collectors are considered (since they are immune to dust storms, clouds, and to some extent, night), Venus receives roughly four times more available solar power than Mars. This is energy needed for regulating temperature, growing plants, and to manufacturing oxygen for continued breathing. Importantly, energy is also needed for any type of economic activity. Moon receives plenty of light, which can be very effectively beamed down from orbital solar collectors as microwaves, or even just reflected down to the surface.

Moon has a resource uniquely its own, which is why it will in truth be the first object with permanent bases. This is that it occupies an intermediate gravity well between Earth and the rest of the solar system, making it an obvious staging point for any non-clown efforts to establish permanent bases on nearby planets.

Venus has the most unique resource of all, in that at roughly 50 km above the surface the atmospheric pressure is 1 bar, basically the same as at sea level on Earth. Coincidentally, the temperature there is around 75° C, firmly below the boiling point of water. These conditions are more Earth-like than anywhere else in the solar system, and the 1 bar altitude will be referred to in this essay as the sweet spot altitude.

When the pressure inside an enclosure is different from that outside, we say that a pressure differential exists, and we know that the walls of the enclosure must be strong enough to resist the net pressure across them. Enclosures designed to withstand large pressure differentials are referred to as pressure vessels, and their shape tends towards cylindrical with semi-elliptical heads, as seen in propane tanks. There are certain human habitations where significant pressure differentials exist, such as airliners, submarines, and spacecraft. These habitations must be built as pressure vessels, which are relatively heavy and usually feature limited living space. The metaphor of living in a tin can works because of the fact that cans are also built to sustain a pressure differential.

At Venus' sweet spot altitude, the air inside a human habitat can be kept at the preferred 1 bar without any pressure differential across its walls. Large habitable volumes are possible even with flat, straight walls —no pressure vessel. The walls only need to keep out the poisonous Venusian atmosphere, so they can be much lighter and cheaper than walls designed to hold pressure. Large habitable volumes will be difficult to ship, but consider that if you are going to Moon or Mars, you also still need to bring everything with you (as with Venus), including the tin cans you will be living in.

Because of the resources of abundant carbon dioxide, potentially abundant renewable energy, and the wide-open interior spaces permitted by a 1 bar atmospheric pressure at altitude, Venus will be the first planet to be settled. Settling means more than just having a permanent manned outpost, as there will be on Moon and Mars; it means having its own, mostly independent, self-sustaining economy. Venus' resources will allow it to grow large amounts of food, which Moon and Mars outposts will engage in trade for. The settlement upon Venus, meanwhile, will engage in trade to feed its insatiable hunger for anhydrous ammonia (which turns out to be something of a Swiss-army-knife type of chemical in this context). As far as the solar system is concerned, Venus will be the new Iowa.

Free Ballooning

The most prominent feature of a recreational hot air balloon is the gigantic lightweight bag which contains the hot air. This is its envelope —which can be defined more generally as the major portion of the body of a lighter-than-air conveyance, where the lifting gas —such as helium, hydrogen, or hot air— is enclosed (that is, enveloped). The wicker basket suspended below it is an example of a gondola. Consider such a balloon in equilibrium with the winds around it; that is, it is traveling at the same speed in the same direction. An observer in an open gondola carried by the balloon will feel no wind on their face, even if the balloon is traveling in very strong winds. This is because the observer is stationary relative to those winds. The observer would sense a breeze, though, when the wind changed speed or direction. Such a free balloon, which will always seek equilibrium with the local air velocity, is not likely to experience strong dynamic loads on its envelope or attachments (except possibly from wind shear).

A dirigible balloon, with engines and control surfaces, is designed to travel in any direction, against the local air current if need be. It may, therefore, experience very strong dynamic loads on its envelope from moving against the wind. A dirigible also requires engine power and fuel to travel, requirements which increase with its mass. Winds are strong upon Venus, a bit above 100 kph at the sweet spot altitude, but they appear to be fairly consistent. The engine power requirements to even influence the location of a large, massive settlement would be quite high, and even if successful would result in large unwanted dynamic loads. It makes more sense to commit to allowing the precise location of the settlement upon Venus to be somewhat random for any given time, and just work around it. The first rule of Venus settlement is that there will be no attempt to fight against the wind.

Ideas in the prior art include Venusian "sky cities," sometimes formed from joined balloons. Some of these are presented as dirigible balloons, which would suffer from the impracticalities described above. On the other hand, if they were free balloons following somewhat random paths through the atmosphere, all at the same sweet spot altitude, catastrophic collisions would not just be likely but inevitable. A consequence of all this is that there can be only one composite balloon upon Venus, one single Venusian continent which grows continuously. This will necessitate that the entire planet's population be able to get along with each other, further illustrating that Venus settlement is only for a *mature* human species. That being said, the economies of scale of a single continent will also come with benefits, such as efficiencies from sharing resources and easy connectivity between regions, and will ultimately generate a greater return on investment.

Venutian Pollution

The permanent cloud cover upon Venus is made up of sulfuric acid droplets, and results in sulfuric acid rain. Because this fact is so very sensational, nearly every description of Venus given in media tends to overemphasize it. The acid is, in fact, saturated; meaning that it is as strong as sulfuric acid can possibly be (which is quite strong). However, there is actually very, very little of it, despite its opacity in the clouds. Temperature and pressure have been the killers of probes we have sent to Venus, not acid, and the science community expects that the acid would be manageable for a human settlement.

A settlement would jealously recycle all materials in its possession, so its occupants probably will not be dumping waste upon Venus. Even if they did, though, it is unlikely that Venus harbors any life which could be harmed by thoughtless human action (though we do not know for sure).

However, there is a form of pollution with which settlers could harm their own progeny very much. The facts that the sulfuric acid is saturated, and that there is very little of it, have the same cause. This is that the limiting factor in its production is the tiny water content in Venus' atmosphere. There will always be enough sulfur dioxide (SO_2) in the atmosphere to guarantee that any additional water will promptly be transformed into the saturated acid. The human presence upon Venus is intended to continue indefinitely, so even a very small rate of water addition to the atmosphere has the potential to add up significantly over time. The second rule of Venus settlement is that a goal of *zero* water addition to the atmosphere must be strictly adhered to at all times.

Furthermore, the high potential for photochemical reactions ensures that any *hydrogen* released into the atmosphere will eventually react with carbon dioxide to generate water. This would be true for ordinary molecular hydrogen (H_2) , as well as for hydrogen bound in a carrier molecule such as ammonia (NH_3) or methane (CH_4). Rocket propellants containing hydrogen (which is most of them) are also ruled out, since they typically have water vapor in their exhaust.

Molecular hydrogen has an extremely small molecule —so small that it is able to leak out of a container right straight through its seemingly solid walls. Additionally, the phenomenon known as hydrogen embrittlement occurs when hydrogen diffuses into the material of a metal (into the spaces in-between its atoms), making it brittle. So hydrogen is prohibitively difficult to contain, not just in its ability to leak, but in its ability to damage metal. As such, even though the use of hydrogen to fill the settlement's balloons would generate excellent lift, without the risk of burning in Venus' carbon dioxide atmosphere, it must never be used in those balloons. They would have a lot of surface area for hydrogen to leak through... and it would.

The comment is often made that normal, breathable air could be used as lifting gas in Venus' heavy carbon dioxide atmosphere. Yes, but no. Note that ammonia (methane also) is a lifting gas in Earth air, but we do not fill blimps with it because it has less than half the lifting capacity of helium, which is available. A normal sized ammonia blimp upon Earth would feature pathetic disposable lift —lighter-than-air lift available for fuel and payload— if it has any at all. So, instead of thinking about inflating Venus balloons with poorly-lifting breathable air, it is better to think in terms of the air filling large habitation volumes as not incurring any weight penalty (as a water environment would if we were fish). It is indeed a good thing when kept in perspective.

An important concept in lighter-than-air is that as the size of a balloon is scaled up, the surface area increases with the square of a characteristic dimension (such as width), whereas the volume increases with the cube. Surface area determines the weight of the envelope material needed to contain the lifting gas, while the volume represents the amount of air that it can displace to generate lift. This square/cube relationship ensures that as the size of a balloon is scaled up, its disposable lift increases much more rapidly than a simple linear relationship.

Because of this, a *very large* ammonia balloon might be sufficiently buoyant to be useful upon Earth air, and would certainly be so in Venus' thick air. Ammonia has the advantage that its molecules can be

contained effectively, unlike hydrogen, and it will be the lifting gas used by all of the settlement's balloons. It still must never be released into the atmosphere, but it has yet another advantage in that it is easily liquefied under moderate pressures at normal temperatures; so that it can be packed away as a liquid, if need be. It is also possible to keep the ammonia lifting gas at a higher temperature than the local atmosphere. Remember that simply raising the temperature of Earth air makes it a lifting gas in other Earth air. Likewise, such superheat of ammonia would increase its lift further, and significantly.

As for helium, note that it is in finite supply on Earth and far rarer than its current cost reflects, due to historical factors. Furthermore, helium is even more of an escape artist than hydrogen, so overall it would be too expensive and difficult to handle for Venusian balloon cells. The choice of lifting gas is important, since an uncontrolled descent towards the surface of Venus would be a horrible thing to experience, whether fast or slow.

Balloon Cells

In the early 1900s, gigantic dirigibles ruled the sky. Germany tops the list for building nearly one hundred of the classic Zeppelins over time, such as the Bodensee and the highly successful Graf Zeppelin. British airships included the R34, which made the first ever non-stop transatlantic flight by dirigible, and the capable R100. The American-built sister ships Akron and Macon were literally airborne aircraft carriers, carrying up to five small recognizance biplanes —launching and retrieving them with a trapeze mechanism. All of these ships fit into the category of rigid dirigibles, since they had an internal metallic framework of transverse rings connected by longitudinal girders. Lifting gas was contained in separate "gas bags" (non-elastic balloons) held inside "gas cells" within the hull. Covering the whole thing was basically tarp.

The balloon cells of the Venus settlement, similarly, will be *rigid* free-balloons, with an outer covering, an aluminum framework, and a dedicated lifting gas container. The shape of a balloon cell will be a hexagonal prism —a box with a six sided cross section— closed on each end by a tri-rhombic cap —a sort of three sided pyramid. This will allow the cells to tessellate —that is, to tile together with no spaces in-between. The width of each cell (for nerds: twice the apothem of the hexagonal cross section) is expected to be one kilometer, while the height (nerds: the distance between the two planes, defined by the three major axes of each of the cap's rhombi) is expected to be one and a half kilometers.

The metallic structure will consist of six major trusses running vertically inside each of the corners of the hexagonal prism, joined along the flat sides of the prism by a plurality of minor trusses. This structure is to bear loads related to connecting the cells and for dynamic loads, not for the loads related to lighter-than-air buoyant lift.

As explained in the engineering textbook Airship Technology (Cambridge Aerospace Series, edited by Gabriel A. Khoury and J. David Gillett), the pressure of the lifting gas at the bottom of a sealed, flexible, partially filled balloon is the same as the barometric pressure of the air beside it. When the balloon is in static equilibrium, this will manifest by the lower surface being drawn up into a flat plane, with any excess envelope material hanging from this "flat." As height increases from the bottom, the pressures of both the lifting gas and the air decrease. The decrease is proportional to the gasses' densities, so the pressure drop of the lifting gas is *less than* that of the air. As such, a pressure

differential develops across the envelope which increases with height. The resulting quasi pressure pushes against the inside of the envelope, most strongly against the top surface.

Inside the familiar "blimp" (a non-rigid dirigible) there are one or two catenary curtains sewn to the top of the envelope on the inside, that taper into a number of catenary cables, from which the gondola hangs. A blimp requires internal gas pressure to maintain the shape of its envelope; it is literally inflated. Still, the lifting gas will expand and contract inside the envelope in response to changes in barometric pressure, which must be allowed for. As such, a blimp envelope contains one or two ballonets —balloons inside a balloon— to hold more or less air from the atmosphere to supplement varying lifting gas volume.

The single lifting gas container of a Venusian balloon cell will be referred to as the gas capsule. It will not share the cell's hexagonal cross section, instead comprising a cylinder to bear the hoop stresses presented by the lifting gas (which increase with the cylinder's height), and a semi-elliptical head on top. The bottom of the capsule can be flat since the pressure there will be the same as local barometric pressure. There will be some arrangement of ballonets at the bottom, which will contain air from the atmosphere, as ballonets do. When possible, they will be filled with CO_2 from which most or all of the acid has been scrubbed, but they must be capable of ingesting untreated air when necessary.

The entire vertical component of the capsule's buoyancy (the technical term is "static lift," but it communicates less well) will act through the semi-elliptical head, in two possible ways. In all cases, catenary cables will be suitably hung from catenary-curtain-like metal structures in the head, traverse the inside of the capsule, and pass through the flat deck to suspend any decks below. In cases where the load is intended to be carried above the capsule, a rigid truss-based structure will transfer load from the decks above down into the semi-elliptical head.

Habitation Decks

The design features three types of balloon cell, roughly correlated to altitude, with all the cells of a given type being mostly identical and mass producible. The three types will have similar components, but with different layouts. Decks which are filled with nitrogen-oxygen air mixtures, and where economic activity will occur, will be referred to as habitation decks.

The type of cells which will operate at or near the sweet spot altitude, and which will make up the Venusian continent, will be referred to as continental balloon cells. Most will feature a general purpose deck in which the cell's specific economic activity or activities will be conducted. In continental balloon cells, this deck will hang just below the lifting gas capsule, and will comprise a roughly five story high empty space with the hexagonal floor plan of the cell, interrupted by periodic "columns," which are actually catenary cables in tension. The space may contain, for example, multiple levels of grow rooms, manufacturing facilities, housing, retail, parks and recreation, or some combination of these and more. Continental balloon cells which are intended to provide extra buoyancy for other cells may feature an elongated lifting gas capsule in lieu of a general purpose deck.

The five story height guideline for the general purpose deck is driven by the recognition that the majority of factories and warehouses used by today's modern society reside within metal box buildings

which are about three stories tall. This is how industry has evolved naturally, and there are practical reasons behind it. Also, many species of tree can grow within a five story limit, allowing there to be parks and other nice spaces potentially within every single balloon cell. Meanwhile, there would be rapidly diminishing returns as deck height increased, since such increases would come at the expense of lifting gas volume. Unlike the many fanciful drawings of steampunk dirigibles, lighter-than-air reality is that an airship must have a gigantic volume in order to have disposable lift, and nearly all of it must contain lifting gas. Transportation within a general purpose deck will be on a "last-mile" basis; for example, bicycles, scooters, skateboards, roller skates, etc.

The lowest deck of all continental balloon cells will be the roadway deck, with an unusual feature. A compass displays the four cardinal directions, North, South, East, and West. Note that these pair up into two lines: N-S and E-W. These cardinal direction pairs will be referred to here as cardinal lines. The roadway deck's unusual feature is that instead of the usual arrangement of two cardinal lines at 90° angles, Venus' hexagonal landscape will feature three cardinal lines at 60° angles. Conceptually, these are all in the same plane, and are: 0°-180°, 60°-240°, and 120°-300°. Each of these three cardinal lines will pass from wall to wall (as opposed to corner to corner) such that each cell contains a one kilometer segment of roadway along each cardinal line. There will be an intersection in the middle, surrounded by a two-dimensional, three-cardinal-line version of a cloverleaf interchange.

The roadway deck will be absent of all pedestrian traffic, and the system will have a steel-wheels-on-steel-rails type of format. In the controlled environment of a balloon cell roadway deck, this will allow smooth rides on trains of grande vitesse.

Unlike the difficult goal of implementing "self-driving" cars in the complicated terrestrial environment, the entire Venusian roadway system can easily be controlled and managed centrally. This centralized control further suggests the railroad format, with steering of vehicles performed externally by track switches. Note that in this context, a rail car could be a single car with its own motor, like a trolley or rail version of a sedan, or it could be like a freight car without a motor, intended to be pulled by a locomotive. A powerful locomotive could pull very many freight cars, functioning as a train, but on the same roadway as smaller vehicles.

In all cases, electrical power will come from an enhanced third rail system. Third rail circuits will only be present in continuous sections of track; that is, they will be intermittent at intersections. Rail cars will not loose power at these break points, using internal supercapacitors —robust devices which store electricity as a static charge, and which can charge and discharge very quickly— to fill in the gaps.

Continental Honeycombs

For the purposes of this discussion, the term honeycomb will refer to a single layer of horizontally tessellated balloon cells. These single layer honeycombs can then be vertically tessellated (stacked). "Tessellation" used here includes the concept of a mechanically strong macro-structure, emerging from the combined micro-structures of individual balloon cells (their major and minor trusses).

The whole reason to settle upon Venus, preferentially over other bodies in our solar system, is its sweet spot altitude. As such, the majority of continental balloon cells in the settlement will be in a single

main layer, such that the general purpose deck of those cells will be located at the sweet spot —this layer can and will be called the sweet honeycomb. In this way, the return on the economic cost of the balloon cells will be maximized, with the consequence that new growth will expand outward into Venus' effectively unlimited sweet spot air space, and generally not upward or downward.

That being said, the design for the Venusian continent does still include other levels for specific reasons. One reason is in support of a very cool feature allowed by the settlement's cellular design: voids. In general, a void is an area where balloon cells are absent from the sweet honeycomb, but with a full layer of honeycomb above and below the void, enclosing it. Each balloon cell remains independently buoyant at all times (with the top honeycomb basically floating, sort of, on the typically breathable air in the void); so there is no need for internal columns, regardless of the void's size or floor plan. The height of a void would be a little under some multiple of one and a half kilometers.

A void could be used as a special, very large park, perhaps with a simulated mountain for climbing and skiing, and small aircraft to fly around in. Another use would be as a hangar to construct new balloon cells, although the logistics of supplying the materials might be very difficult. Note that this incredible potential for a space which is gigantic, wide open, entirely habitable, and economically viable can only occur when the outside barometric pressure is 1 bar. The only two bodies in our solar system where this condition exists, together with reasonable temperature and gravitational conditions, are Earth and Venus.

Below the sweet honeycomb, there will be a sparse, but still extensive basement honeycomb. These will be continental balloon cells, usually with an elongated gas capsule and no general purpose deck, and with their own collective roadway deck. A major purpose of the basement level is to add rigidity to the continent as a whole. Another purpose is to function as the bottom enclosing honeycomb of a void, becoming its floor and buoyantly lifting items contained inside the void. A continental cell in the basement honeycomb may also be used to add extra buoyancy below a sweet honeycomb cell which may be especially heavy, for example one housing heavy manufacturing equipment.

Above the sweet honeycomb there will be another sparse level of continental balloon cells, the upper honeycomb. The main purpose will be to function as the top enclosing honeycomb of a void, becoming its ceiling. A more fanciful use can be imagined after a century when the continent is very large. This would be to house, in the cells' general purpose decks, a network of supersonic transport tubes. These tubes will not share intersections in each cell like the roadway decks, but instead be separated into three layers, with each layer servicing a cardinal line.

For roadway vehicles to move between honeycombs, they will need to rise or descend vertically by one and a half kilometers. This travel will occur in the major trusses, where there is room for some advanced type of freight elevator without intruding on lifting gas containment. Still, it will usually be preferable for vehicles to remain on a given honeycomb.

Canopy and Tether Buoy Honeycombs

The unique conditions upon Venus allow all of the energy needed by the settlement to be derived from perpetually renewable resources. There are three resources available, and they all favor the addition of

a single honeycomb, connected to the continent, but kept at a very high altitude. The specialized cells of this honeycomb will be referred to as canopy balloon cells, and when joined together will result in the canopy honeycomb.

Ideally, the canopy will have a larger diameter than the continent, and it will be "held captive" above it by numerous tether conduits —essentially cables, integrated with a tubular, protective conduit. Together, the continent and canopy will basically constitute a balloon holding a balloon. Many of the tether conduits will contain fluid flows related to energy generation (described below), and a few will function as elevator shafts. All of them will carry electrical power.

The target altitude for the canopy is 65 kilometers, with the goals of being above most of the clouds and in the coldest air possible. It is important to recognize that the amount of lift a given balloon can provide decreases *exponentially* with altitude. To maximize the altitude of the canopy, only the necessary weight of energy generation equipment will be allowable (analogous to the "height-climber" Zeppelins of WWI). Citizens will likely demand an exception for observation decks around the perimeter (perhaps with limited-stay, overnight sleep pods), since it would be the only place upon Venus with a decent view, usually staying above the clouds. Note that humans at the canopy altitude will need to be inside either a pressure vessel or a pressure suit. The habitation decks themselves will still be designed to have no pressure differential against the low barometric pressure outside.

The canopy balloon cells will have their general purpose deck at the very top of the cell. It will have a flat, usually transparent ceiling (as opposed to a tri-rhombic cap). Underneath this deck will be a roadway deck, as usual. The lifting gas capsule will have few catenary cables (mostly to suspend the ballonets), since the weight of the roadway and general purpose decks will be borne on top of the capsule's semi-elliptical head. There will be a tri-rhombic cap on the bottom, with a tether conduit attached in most cases.

The canopy's general purpose deck will usually house solar-tracking photovoltaic collectors, one of the settlement's three energy sources. At the top will be a sparse grid of wires, which constitute a second energy source. These will function collectively as a rectenna (rectifying antenna) —an antenna which receives a beam of microwave energy and converts it into electricity. The microwaves would be beamed down from orbiting solar collectors. This idea is in the prior art, since it was first proposed to provide power on Earth, where it would be an absolutely bad idea. (Upon Venus there would be no birds to be cooked in mid-air ;)

The tether conduits, being perhaps fifteen kilometers in length, will be fairly heavy. In order that the canopy cells do not need to bear the majority of this weight, there will be a sparse honeycomb of tether buoy balloon cells to do so. This will be at an altitude which presents a balance between being in dense air, in order to be able to lift significant weight, and keeping the length (and weight) of the tether conduits above it to a minimum. Tether conduits will be held along the *corner edges* of the tether buoy cell's hexagonal prisms. Flat tops and bottoms will allow the single-layer tether buoy honeycomb to be slightly more aerodynamic than tri-rhombic caps would be. There will be a roadway deck in this honeycomb, but no other habitation. Some specialized tether buoy cells will feature general purpose decks involved with energy generation, in lieu of attachments to tether conduits.

Note that the continental honeycombs, tether buoy honeycomb, and canopy honeycomb will all be at altitudes with different prevailing wind speeds. The continent will be the one to catch the most air, and will dominate the overall movement. The tether conduits must be strong (and redundant) enough to pull along the higher honeycombs, and will themselves generate a lot of drag. Importantly, the dynamic loads acting on these bodies will be a function not just of wind speed, but also of air density —which decreases exponentially with altitude. As such, high apparent wind speeds at high altitudes will impart much less force than high apparent wind speeds at low altitudes.

Cytherean Thermodynamics

Heat is a type of energy, but its energy is not necessarily available to do useful work. The Carnot efficiency equation gives the ideal maximum percentage of heat energy which can be converted to useful work in a heat engine. Significantly, it depends *only* on the temperature difference between the hot heat source and the cold heat sink. There is a significant temperature difference between the continental and canopy altitudes (about 100 Celsius degrees, for a Carnot efficiency around 30%), and so it is certain that this can be exploited in one way or another to generate electricity.

The third source of energy for the settlement, then, will be a working-fluid based heat engine analogous to true geothermal energy. The core element of this system will be referred to as a cythermal engine, where heat addition occurs near the sweet spot altitude, and heat rejection occurs at canopy altitude. It will use CO_2 as working fluid in a closed cycle, pressurized on the order of tens of bars so that it will condense into liquid (as opposed to depositing as dry ice), and will do so at canopy temperatures. The liquid CO_2 will then be boiled at continental altitude temperatures (Rankine cycle with reheat) and drive an electrical generator. The CO_2 plumbing traversing the continent and canopy altitudes will be contained in tether conduits, be roughly fifteen kilometers in length, and must be thermally insulated very well (ideally adiabatic).

Each cythermal engine will have a condenser (heat exchanger) and heat vent in the general purpose deck of a canopy balloon cell (at top). This will allow heat rejection at the lowest temperature possible. It is likely that this equipment will be heavy enough to require the full disposable lift of the cell, obviating the presence of solar collectors in these specialized cells. There can be any number of cythermal canopy/continental cell *pairs*, each constituting a power generation plant.

Venusian Aikido

In accordance with the way of harmonious energy, the normal operation of a cythermal engine power plant will also function as the first step in a mechanism to extract useful gasses from the atmosphere. The overall process, proposed in this essay, will be referred to as Venusian air commodification —where atmospheric air is drawn in, nearly all of the non-CO_2 components are extracted, and the excess carbon dioxide vented back to the atmosphere. Some purified CO_2 will be retained, being the most important commodity extracted, with molecular nitrogen the next most important commodity.

Fractional distillation is predominantly the process of separating a liquid into sets of components, called fractions, where the components in a fraction all have nearly the same boiling point. This involves

boiling the liquid first, where the boiling itself can be used to separate two fractions. When gasses (such as air) are being separated they are sometimes fully liquefied first at cryogenic temperatures, and then selectively boiled into fractions (Linde process).

The first step in Venusian air commodification will instead be referred to as fractional condensation, in order to emphasize that the air to be separated will begin as a gas (far from its boiling point), and will include the concept that the condensation process constitutes the source of heat addition for a single cythermal engine. The air to be separated will be drawn in at the lowest altitude practicable, in order to allow heat addition at the highest temperature possible.

Fractional condensation will occur inside a highly insulated, and long, fractionating duct —a duct with a series of sections designed to maintain a progressively lowering (with height), and specific, temperature in each section. It will include provisions for the collection of any liquids which condense out in that section. Temperature will be controlled using the CO_2 working fluid of the cythermal engine as refrigerant, in turn boiling the CO_2 as part of the energy generation mirror process. As such, the fractionating duct will be limited to targeting air components with a boiling point higher than carbon dioxide; which include water (along with any dissolved acids), sulfur dioxide, and hydrogen fluoride.

The remainder of the air commodification process involves an exhaust stack —a duct inside a tether conduit where the excess carbon dioxide to be vented goes through several cycles of heat addition, gas expansion, and work extraction (Brayton-ish cycle). This will occur at progressively higher temperatures, as waste heat accumulates. Work extraction will be done by exhaust turbines —pairs of counter-rotating "wind turbines" inside the exhaust stack which generate electricity. The air flowing through the stack will be mostly pure carbon dioxide, entering into the stack near its closed bottom. Here it will be reunited with its own original heat, plus the original heat of commodity gasses removed, plus waste heat from refrigeration systems used on the continent (which will avoid the direct use of CO_2 refrigerant for safety reasons).

The gasses remaining after fractional *condensation* will be fully separated by generic fractional *distillation*. These will include nitrogen, argon, helium, neon, and hydrogen chloride. First, however, the bulk carbon dioxide in the remainder gasses will already be close to its boiling point, and can be separated out, perhaps, by passing the gasses through an expansion valve (possibly resulting in deposition).

The process begins with remainder gasses, possibly from multiple cythermal engines, collected in specialized cells within the tether buoy honeycomb. They will then be compressed intensely by electric compressors, and sent to heat exchangers in the stack to recover as much heat as the local stack temperature will allow. Further heat rejection will be accomplished by then passing those gasses through heat exchangers at canopy altitude.

It is expected that the habitation decks will require constant heat removal, due to heat infiltration, biological activity, and economic activity. By using the stack as a heat engine, a *portion* of the energy used in air separation and habitat climate control can be recaptured (minus the entropy tax sent to Mssrs. Carnot and Boltzmann). At the altitude where the tether conduit will be attached to a sweet honeycomb balloon cell, there can be solid-state, conductive heat exchangers penetrating into the stack. The still-hot air at that altitude can add heat for another work extraction cycle.

Note that the outlet of the stack will be at canopy altitude, in the low pressure atmosphere there. Put another way, the column of air above the gasses in the stack will not be pushing down on them very hard. Still, it is important that the exhaust stack be thermally well insulated (ideally adiabatic), so that exhaust gas does not cool and become heavier (more dense).

Cell Manufacture

It turns out that Moon's surface contains a fair amount of aluminum, iron, and silicon ores. Here also orbiting solar collectors are feasible for both refining ore and manufacturing balloon cells. Balloon cells will be manufactured from the top down, such that the completed portion of a cell is continuously raised by a gantry, and the outer covering, truss-work, and lifting gas capsule added to it as it goes. The capsule will be 3D printed using a process where a metallic wire is continuously welded to the circumference of the growing article. By lifting the balloon as it is added to, all of the welding and assembly equipment can remain at ground level.

The vacuum of Moon will allow the rigid structure of the gas capsule to be free of a pressure differential, even as the ballonets are completely deflated. Because of the complications of catenary cables and such inside the capsule, it will not be possible (nor desirable) for the ballonets to entirely fill it. Cell manufacture inside a continental void will occur submerged in a nitrogen/ oxygen mixture, and so upon completion the gas capsule will require a complicated process to replace the mixture with ammonia lifting gas. Moon's vacuum permits manufacture without this process.

Ideally, new cells would be shipped from Moon in sets of two or three. These could be a set of three continental balloon cells, or it could be a set of two consisting of a continental cell tethered at the factory to a canopy cell, with the coiled tether conduit riding between them. Packaged with a set would be a sizable quantity of anhydrous ammonia, kept as liquid under pressure.

This ammonia will be used as the lifting gas to fill the cells upon arrival, but it will also be needed for other purposes. Chief among these is the manufacture of water. With both energy and carbon dioxide abundant to the settlement, oxygen will be easy to manufacture. The weight of this oxygen will not need to make the trip from Moon, but the hydrogen in the ammonia will, and can be combined with the native oxygen to make water. The byproduct, normal molecular nitrogen (N_2), will always be welcome in settlement upon Venus. Meanwhile, the ammonia can also be used as fertilizer to grow food, which is intended to be the settlement's primary economic activity.

A spacecraft cannot "re-enter" the atmosphere of a planet it has never been to in the first place; instead it aerobrakes. For the proposed truly gigantic sets of balloon cells, there must be an even more gigantic heat shield. Another well known use of ammonia is as a refrigerant. Upon aerobraking, the liquid ammonia carried by the shipment can be used as refrigerant to actively cool the heat shield, boiling into gaseous ammonia in the process and inflating the balloon cells as it goes. Inflation will occur in concert with the descent into thicker air, such that no excessive pressure differentials develop (moderated also by the ballonets).

Due to the volume of the cells and the quantity of ammonia gas needed to fill them, it is likely that the heat shield will actually remain quite cold during the whole aerobraking operation. This will facilitate

the multiple re-use of the heat shield. Once the dish-shaped shield has unloaded its cargo, it can expand its top surface by inflating with more ammonia (into a lens shape). Because of the size of the shield, it will be easy to make it very much lighter-than-air to prevent it from being accidentally lost to the depths. Reusable rockets from the continent would then push it back into orbit to be reused.

Venerean Rockets

If the goal is for Venus to feed the solar system, there must be a cost effective way to ship their products. One of Venus' advantages is that it exerts about 91% of the gravity of Earth. This is good because that is close to what our bodies evolved for, and we know that microgravity, at least, is debilitating and even deadly over time. However, this means that launching rockets into Venus orbit will be at the same level of difficulty as for Earth. The first additional problem, though, is how to obtain rocket propellants (fuel and oxidizer) in industrial quantities. Venus has abundant carbon dioxide and solar energy, so we can have unlimited amounts of graphite and liquid oxygen propellant combination. This is not very promising, but sadly, nothing else is realistically available. At least it would not add water to the atmosphere. We will call the propellant combination graphlox in accordance with convention.

Before we even get to the fact that graphite would be very difficult to burn at all, let alone to burn fast enough to produce thrust, the other critical rocketry metric would certainly be very poor for graphlox. This metric is specific impulse, and it is a measure of how efficiently a rocket system uses the mass of its limited, carried-on-board propellant to generate the acceleration needed to reach orbital velocity. Even though the combustion of carbon can release a fair amount of energy, it is very massive compared to fuels with hydrogen in their molecules. The end result is that a solely graphlox rocket is not likely to be able to achieve Venus orbit under any circumstances (staging, single use, etc.).

As noted earlier, it is possible to transmit energy by concentrated microwave beams; for example, from orbiting solar collector satellites. Energy added to a graphlox system from microwave beams would not weigh anything sitting in tanks on board the spacecraft, so it would increase the effective specific impulse of the combined cycle. There would be the added weight of a rectenna and a need to design the rocket vehicle in a manner that accommodates that rectenna. However, these masses will be constant, and not subject to the exponentially-driven phenomena known as "the tyranny of the [Tsiolkovsky] rocket equation." This mathematical tyranny really only applies to the mass of propellants sitting in tanks. Propellant is needed to lift the sitting propellant before it is burned, then more propellant is needed to lift that propellant, and so on.

The question then becomes how to apply such microwave energy to the production of thrust. There are somewhat prosaic methods available (in the prior art), such as "electrothermal thrusters," but the chemistry of graphlox actually offers a unique method. A fuel and air mixture can exist, without being on fire, because a significant amount of energy is required to split apart the molecules of fuel and the molecules of oxygen (O_2). Once an "ignition source" provides this activation energy, the atoms can re-arrange into exhaust molecules, releasing energy as heat in the process. The heat released is more than enough to provide continuous ignition, but the temperature produced is actually slightly lower than that released, because some of that heat energy is absorbed to provide further activation energy.

So let's kill two birds. Graphite does not burn well, but it is great at being an electrode. So we can use the microwave-derived electricity to pump electrons out of it. We can give those electrons to a stream of molecular oxygen molecules. Because oxygen *really* likes electrons (it has a high electronegativity), it should not be too difficult to produce single-atom oxygen ions, thereby providing its activation energy before combustion. When this stream of electric oxygen is introduced to the positively charged solid fuel electrode, it should burn readily. Any extra energy contained in the electrical potential should also end up as additional heat.

One possible implementation is to set up the reaction to favor carbon *monoxide* (CO) as a product, resulting in a pipe-transportable fluid to be burned to completion in a combustion chamber elsewhere. This carbon monoxide could then be used in a reaction control system —that is, the system of maneuvering thrusters required in spaceflight. Also note that microwave electricity can be used to drive propulsive fans, perhaps as part of a "combined cycle" propulsion system (or maybe turbo-compressors, followed by electrothermal heat addition). Such a system would allow a spacecraft, configured as an aircraft with aerodynamic lift, to traverse and exit the dense parts of Venus' atmosphere before any stored propellant is consumed.

A fully developed graphlox+microwave technology, taken in the context of Venus' very specific case, will likely permit single-stage-to-orbit spacecraft, and result in a cost-per-mass-to-orbit that is much lower than will ever be possible for Earth. This is because microwave energy transmission in the very busy atmosphere of Earth is an *absolutely bad* idea.

Mercury for Dinner

Fun fact: the sun's gravity at the distance where planet Mercury orbits is strong enough that relativistic effects are actually significant. Furthermore, Mercury has the highest orbital speed of any planet, so joining it in its orbit requires a spacecraft to carry and burn a lot of fuel (generally subject to the Tsiolkovsky equation). Additionally, it is really hot where Mercury is. The combination of these factors make Mercury notoriously difficult to get to and still fairly mysterious.

Venus has the advantage over Earth that its orbital speed is more closely matched to Mercury's. A Venus settlement would have an incentive to go there too, since mining Mercury might actually be easier for it to achieve than mining Venus' planetary rock just below them. Part of this is due to Mercury's ironically more manageable thermal environment, and part of it is that it appears that much of its crust may have been ripped away in a distant past collision with a planetesimal. As such, Mercury's metallic core appears to be very much closer to the surface than on Venus, and could be a great source of iron, nickle, other metals, and of course silicon.

Also ironically, it is believed that a large amount of water ice may be present in Mercury's polar craters, shielded from direct sunlight by the crater walls, and with no atmosphere to conduct heat by convection. Addition of all of these materials into the economy of Venus would greatly help to support its manufacturing sector, and maybe even build it an artificial moon. As though adding a new chapter to classical mythology, it is likely that ultimately, Venus will devour Mercury.

Conclusion

I first learned about the idea of "colonizing" Venus with balloons roughly a decade ago, from a video on the greatest-of-all-time YouTube channel —PBS Space Time— entitled Should We Colonize Venus Instead of Mars. I had already had a long-time, deep interest in dirigibles and lighter-than-air technology. As part of this aerostatic self-study, and long before the video, I had come up with the idea of these interlocking hexagonal rigid balloon cells; albeit in the context of a floating city upon Earth. This was mostly just for fun, since the actual rarity of helium on Earth would be an absolutely prohibitive cost. (At least until we could first go out into the solar system —Jupiter— and somehow retrieve some of the universes' abundant primordial helium.) Of course, the PBS Space Time episode provided a much better hypothetical application for interlocking hexagonal balloon cells.

There are multiple other YouTube content creators who have made similar great videos about Venus and the potential for its settlement; for example, engineer Scott Manley with Can We Explore Other Planets With Balloons. Also notable for YouTube coverage of Venus are screenwriter Joe Scott with NASA's Plan to Build Cloud City On Venus, and historian Amy Shira Teitel (The Vintage Space) with The Post-Apollo Human Mission to Venus. Even NASA has a video presenting a study it did called the High Altitude Venus Operational Concept, or "HAVOC," which outlined a hypothetical future manned mission to Venus.

YouTube futurist Isaac Arthur (Science & Futurism with Isaac Arthur) provides his characteristically well-researched discussion on the topic of Venus in his videos Colonizing Venus and Winter on Venus. I am a fan, but these videos infuriated me! He seems to favor terraforming Venus as opposed to settling it as it is. Unfortunately, terraforming would require that a large amount of Venus' carbon dioxide atmosphere be removed in order to make barometric pressure on the surface survivable. One such idea mentioned is to "blow away" Venus' atmosphere into space, for the sake of living on the rock below. What is the economy going to be on this probably volcanic, very dry rock? Why needlessly force the ridiculously slow rotation of Venus' planetary rock (a Venus day is longer than its year) to be a problem when it doesn't need to be? What narrow-focused "surfacism" should encourage us to destroy any portion of Venus' valuable carbon dioxide resource?

Much of the prior art discussing human occupation of Venus includes another particular silliness. They always *talk* about the sweet spot altitude, seemingly implying that it is the goal, but they always *show* a dirigible or balloon high above the clouds. As noted earlier, lighter-than-air buoyancy decreases exponentially with altitude; so there will be no settlements high above the clouds. Furthermore, it is important to emphasize that the sweet spot altitude is right smack in the densest part of Venus' acid permacloud. Any windows at that altitude will only ever look out onto the fog of cloud. This fog will alternate between bright orange and pitch black, but it will never be sensational.

Dedicated to Dr. Carl Edward Sagan, 1934-1996
—
astronomer, custodian of Earth, and
the original on-Tube science communicator